Geographical and Orbital Information Based Mobility Management to Overcome Last-Hop Ambiguity over IP/LEO Satellite Networks

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***Abstract*— Low Earth Orbit (LEO) satellite networks are well characterized by frequent and bursty handover occurrences, and these handovers largely affect the cost of mobility management in LEO satellite networks. Although geographical location of a mobile node is useful information to make the mobility management independent from handovers, it is difficult to decide a last-hop satellite of the node based only on geographical location information. This last-hop ambiguity problem needs additional cost to find the real last-hop satellite. To reduce last-hop ambiguity, we propose to exploit orbital information of the satellite connected with a destination node in addition to geographical location information.**

Simulation results shows that the number of last-hop candidates and hop counts between candidates are reduced by introducing orbital information. Through a mathematical analysis, we evaluate the cost required for mobility management and show the effectiveness of the proposed method.

I. Introduction

In this paper, we propose the efficient mobility management scheme dedicated for IP/LEO satellite networks. In the future IP/LEO satellite integrated networks, a user terminal can have a functionality for connecting both terrestrial and LEO satellite networks, and users can move freely in the integrated networks. Thus, mobility management is one of the important processes. In those networks, we need to consider three types of user movement. These are movement on terrestrial networks, movement from terrestrial networks to satellite networks or vice versa, and movement in satellite networks. Mobile IP (MIP) [1] [2], a standard mobility management scheme for the Internet, is a candidate for supporting the first and second types of node movement. However, considering the characteristics of LEO satellite networks, supporting mobility in satellite networks with MIP is difficult [3]. In terrestrial mobile networks, only end nodes are subject to motion while base stations remain fix. Whereas, in LEO satellite networks, both end nodes and satellites (base stations) keep on moving. Furthermore, satellite networks cover wide areas and should consequently serve a potentially large number of end nodes. This compels LEO satellite networks to operate under high-mobility conditions and makes them experience bursty handovers that do not occur in terrestrial networks. To overcome this issue, a dedicated mobility management scheme for LEO satellite networks is needed.

In [3], we have proposed that utilization of geographical location information (GeoLoc) as a routing identity [4] of an end node, in order to support mobility in LEO satellite networks. By doing this, routing identity of an end node is entirely independent of handovers, and we can give an illusion of a low-mobility characteristic to LEO satellite networks. However, the use of GeoLoc causes another problem of "Last-Hop Ambiguity". In LEO satellite networks, most users are covered by multiple satellites and all satellites are considered as last-hop candidates of a user. This means that it is difficult to decide a last-hop satellite of a node based on GeoLoc of the node. Although local forwarding and paging are used in [3] for tackling this problem, the cost needed for such procedures increases when the number of candidates and hop counts between the candidates are large. To reduce the cost, we propose to introduce orbital information of the satellite connected with a destination node into the node's routing identity. Orbital information is a topological information in LEO satellite networks, and it is useful for reducing last-hop ambiguity. Reduction of last-hop ambiguity leads to decrease both occurrence of local forwarding and its cost.

The rest of the paper is organized as follows. Section II-B explains the last-hop ambiguity problem in LEO satellite networks and its effect on the mobility management scheme using GeoLoc. Section III presents the proposed scheme which can overcome the last-hop ambiguity problem in LEO satellite networks. Section IV analyses the cost of the proposed method. Section V shows evaluation result in terms of mobility management cost. Concluding remarks are in section VI.

II. Mobility Management over IP/LEO Satellite Networks

A. Overview of the Mobility Management over IP/LEO Satellite Networks

Mobility management mainly consists of two procedures, namely binding update and data delivery. Therefore, mobility management and routing are closely related processes. In the current LEO satellite networks related research area, research

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about routing protocol go before mobility management research. For example, routing based on geographical position of a node [5], routing based on logical location of the satellite [6], and multicast routing protocol based on logical location of the satellite [7] have already been proposed. However, for realizing IP/LEO satellite integrated networks, an efficient mobility management protocol is also needed.

As previously mentioned, IP/LEO satellite networks inherently have high-mobility characteristics. Existing global mobility management schemes for terrestrial IP networks (e.g. MIP, MIPv6) assume low-mobility environment where MNs do not perform binding update so frequently. Thus applying such schemes to LEO satellite networks is an inappropriate solution. To tolerate frequent MN's movement, some local mobility management [8] protocols using micro mobility concept (Hierarchical MIP (HMIP) [9] and Cellular IP [10]) are proposed. Those protocols are sufficient for supporting rapidly moving MNs (e.g. vehicles, motorcycles) in terrestrial mobile networks, but we insist that their cannot avoid bursty handover occurrence in LEO satellite networks. This is because that movement of satellites served as ARs is faster than any terrestrial MNs, and the size of coverage area of a satellite is huge. Consequently, we need and focus on the localized mobility management [8] scheme dedicated for high-mobility environment in LEO satellite networks. Note that our target is to support the third type of mobility mentioned in Sec. I (i.e. movement in LEO satellite networks), and other two types of mobility are assumed to be supported by global mobility protocols such as Mobile IP and Mobile IPv6.

B. The Last-Hop Ambiguity Problem

For avoiding bursty binding update occurrences in high-mobility LEO satellite networks, we have proposed GeoLoc based mobility management scheme and shown the effectiveness in [3]. However, using GeoLoc as a routing identity of a node causes another problem, so called "Last-Hop Ambiguity". Although a certain geographical area can be covered by multiple satellites in LEO satellite networks, a MN usually selects and uses one satellite for communication. That satellite is the last-hop satellite of the mobile node. If a destination node is located only by GeoLoc, we have to find the last-hop satellite connected to the destination node among the multiple last-hop candidates. For delivering a packet to the real last-hop satellite, a local forwarding scheme and a paging scheme are used in [3]. However, in the case that the path between last-hop candidates is long, the cost for the local forwarding and the paging is high. For example, in the Walker Delta Constellations [11], if geographically close two satellites belong to different directional (i.e. ascending and descending) orbit, the path between those satellites often has large hop counts. This is because there are no inter-plane inter satellite links (ISLs) between ascending and descending satellites, and the traffic between the satellites must travel over the highest latitude inter-plane ISLs [12].

We show the last-hop ambiguity characteristic in a Walker Delta Constellation through a simulation using NS-2 [13]. In this simulation, the Next generation LEO System (NeLS) [14], which is a kind of Walker Delta Constellation developed in Japan, is used. NeLS consists of 120 satellites on 10 orbits. Altitude of satellite is 1,200 kilometers and the orbit inclination is 55 degrees. NeLS covers the region from latitude 60 degrees north to latitude 60 degrees south. Figure 1 shows the average number of satellites covering a square-shaped cell. The cell length is measured in degrees. X-axis in the figure shows latitude of the cell. As shown in the figure, a cell is covered by two or more satellites in any latitude. Figure 2 illustrates the average hop counts between two satellite covering a same cell. The hop counts take large values especially in low latitude regions because of absence of ISLs between ascending and descending satellites.

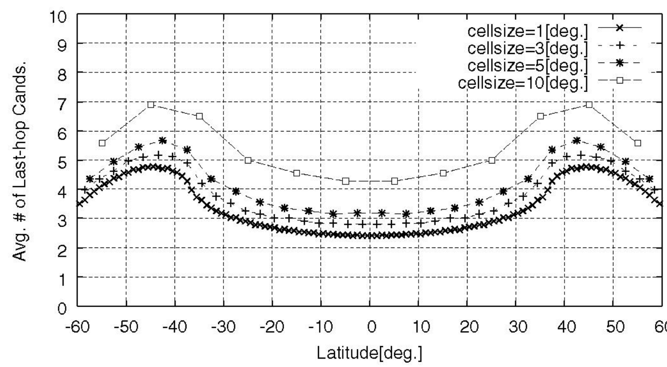

Fig. 1. Average Number of Last-hop Candidates (without Orbital Information)

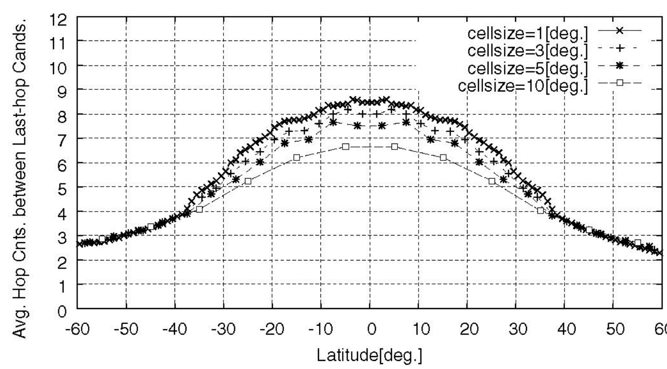

Fig. 2. Average Hop Counts between Two Last-hop Candidates (without Orbital Information)

To tackle the last-hop ambiguity problem of LEO satellite networks, we propose the use of both geographical and orbital information for locating a MN.

III. Combination of Geographical and Orbital Information for Mobility Management

In this section, we give a detailed description of the proposed method. The core idea of the proposal is to utilize orbital information together with geographical information, depending on the node's communicating status. The proposed method gives different routing identities to an *idle* node and an *active* node. In addition, the local forwarding and paging are used for solving last-hop ambiguity in a similar way as in [3].

A. Introducing Orbital Information

Here, we propose mobility management scheme combining geographical location and orbital information. The proposed method is for alleviating the effect of the last-hop ambiguity problem caused by geographical location based mobility management. In the proposed method, the routing identity of a node is composed by the following information:

- GeoLoc: graphical location information of the node,
- OrbitIDX: Index of the orbit which the last-hop satellite of the node belongs to.

A LEO satellite network consists of multiple orbits, and every satellite belongs to one orbit. Obviously, the proposed method assumes that a MN can acquire the orbit index (OrbitIDX) of the connected satellite. Since the OrbitIDX of a satellite is invariable, the satellite can easily know the OrbitIDX and can provide the information of the OrbitIDX to connected MNs.

By introducing OrbitIDX in order to locate a MN, last-hop candidates of the MN are limited to only satellites belonging to the same orbit. As a result, both the number of candidates and hop counts between the candidates are reduced. Since increasing the number of candidates and hop counts makes the cost for local forwarding and paging high, the proposed method contributes to avoid the cost increase.

Figure 3 illustrates the concept and the merit of the proposed method. Suppose that one MN is in a geographical cell, and four satellite in two orbits cover the cell. The MN connects with one of the satellites in the orbit B, thus the satellite is last-hop satellite of the MN. Although all of the four satellites are last-hop candidates in the existing method, the proposed method can limit last-hop candidates to the satellites belonging to the orbit B.

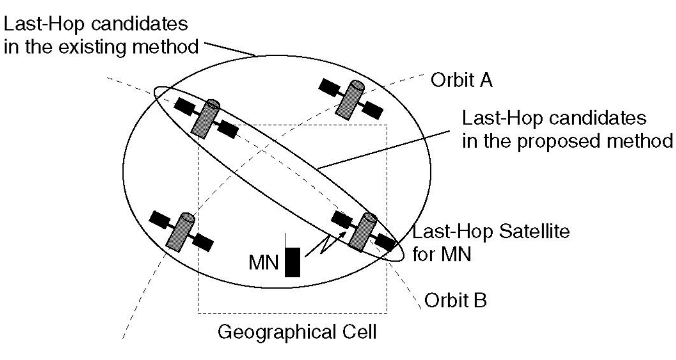

Fig. 3. Concept of the Proposed Method

Figure 4 illustrates the effect of introducing orbital information in the NeLS constellation. This figure shows the average number of satellites belonging to a certain orbit and covering a square-shaped cell.

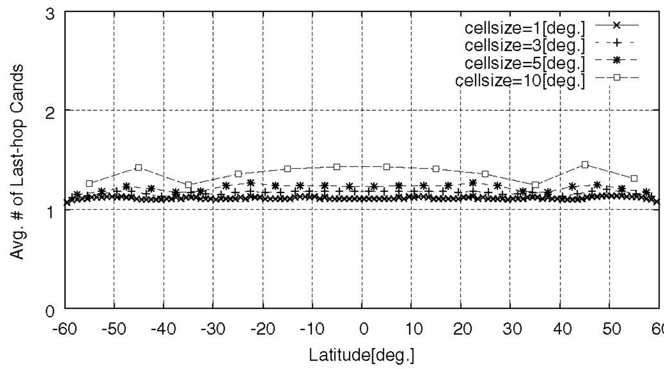

Fig. 4. Average Number of Last-hop Candidates (with Orbital Information)

It is clear that the number of last-hop candidate satellites is limited to one in most cases by using orbital information. Therefore, average hop counts between last-hop candidates is almost zero. Consequently, introducing orbital information can solve the last-hop ambiguity problem.

B. Node Status Dependent Routing Identity

In the proposed method, the routing identity of a MN depends on the communication status of the node in the proposed method. All of the nodes are categorized as *idle* or *active* according to their communication status. An idle MN is a MN which is not sending or receiving any data during a certain period. An active MN is a node which is communicating with other nodes.

To support a large number of mobile nodes, usage of IPv6 [15] is seem to be very appropriate for IP/LEO satellite networks. The following is the basic structure of IPv6 address.

IP Address = Prefix + NodeID.

The proposed method gives different types of Prefix to idle or active MNs. While prefix of an idle MN includes only GeoLoc, prefix of an active node has both OrbitIDX and GeoLoc. These are summarized as follows.

- For idle nodes:
  IP Address = Prefix(GeoLoc) + NodeID,
- For active nodes:
  IP Address = Prefix(OrbitIDX, GeoLoc) + NodeID.

Basically, packets toward active MNs need more routing accuracy rather than packets toward idle MNs. The orbital information in the routing identity of active MNs can increase routing accuracy by decreasing last-hop ambiguity as mentioned in Sec.III-A. The proposed method assumes that the OrbitIDX is advertised by the connected satellite. Therefore, an idle node cannot use the orbital information because the idle MN is not connecting to any satellites. All MNs are assumed to be equipped with GPS like device for getting GeoLoc.

Inclusion of GeoLoc into a prefix has been considered in a routing related work [16]. In [16], the GeoLoc is represented in 44-bits field to provide a resolution grid of approximately 6.4 meters on a side. To include the OrbitIDX into the prefix, we use 8 higher-order bits of the 44-bits field. By doing this, the proposed method can be applied to the LEO constellation composed by 255 orbits in maximum. Since all of the existing constellations have at most several tens of orbits, this would be the reasonable setting even in the future. Note that all of 8 higher-order bits set to 0 if a MN is idle. For the GeoLoc, remained 36-bits can provide a resolution grid of approximately 102 meters. According to our previous results [3], an appropriate geographic cell length is in the order of hundreds kilometers on a side. Hence, 36-bits are enough to represent an appropriate size of geographic cell. NodeID is used to identify a node in a cell. In order to avoid changing the NodeID when a node moves into a neighboring cell, NodeID should be globally unique.

When a MN moves to a neighbor geographic cell, regardless of its communication status, the MN's GeoLoc is changed and the MN must perform binding update to a local Location Directory (LD) in LEO satellite networks. It is clear that this binding update event is handover independent, and bursty binding update occurrence can be avoided by the proposed method as well as the geographical location based scheme [3]. Only for active MNs, OrbitIDX changes when nodes handover to a satellite belonging to the different orbit and the active MNs have to perform binding update at that time. Although such inter-orbit handover occurs not so frequently compared with intra-orbit handover, the proposed method may suffer from bursty and frequent handover occurrence in the case that most of nodes are active. Therefore, the effect of the ratio of active MNs is considered in the performance evaluation shown in Sec. V.

C. Local Forwarding and Paging Schemes

Local forwarding is used for delivering the packet to the active node after a handover. After an active node handovers, the new satellite which is connected with the node informs the old satellite that the node has indeed performed a handover. In response to that, the old satellite forwards the packets to the new satellite, when the old satellite receives the packet destined for the node.

In the proposed method, local forwarding is always performed between the satellites belonging to the same orbit. Therefore, the local forwarded packet experienced the small hop count compared with the case of the existing method. This results in a reduction of the cost for local forwarding.

In addition, when the new satellite begins to cover a cell and becomes a last-hop candidate of the cell, that satellite has to inform other candidates of its existence. Then, the candidates including the new satellite exchange the covered active nodes list among each other.

Paging is used for finding the last-hop satellite of an idle node. In the proposed method, the last-hop candidates, satellites that cover a single cell specified by the GeoLoc, broadcast paging messages. While satellites broadcast paging messages in their coverage, only MNs in the cell indicated by the prefix of an idle node's IP address check paging messages. The proposed method considers thus each cell as a single paging area.

IV. Analysis of Mobility Management Cost

In this section, we evaluate the factors that influence the cost needed by the mobility management task. In [17], the management cost is computed as the product of the generated control message size, M, and the number of hops, H, required to deliver the message. Using such definition, we derive the equations to calculate the cost incurred by the signaling of binding update, local forwarding, and paging. For simplicity, the size of control messages, M, is assumed to be equally sized in the three events.

A. Binding Update

Let $H_{MN,LD}$ denote the number of hops between a MN and a LD. The cost for a binding update procedure can be expressed as $2 \cdot M \cdot H_{MN,LD}$. The cost equation counts the cost of both request and response signaling.

In the proposed method, all nodes perform binding update when the geographical position is changed by moving to a neighbor cell. Additionally, only active nodes perform binding update when the node handovers to a satellite belonging to different orbits. Therefore, the frequency of binding update performed by nodes in a cell, R_{BU} is shown as follows:

$$R_{BU}(t) = R_{CC}(t) + R_{OHO}(t) \cdot \alpha \tag{1}$$

where $R_{CC}(t)$ and $R_{OHO}(t)$ denote cell crossing rate and rate of handover between satellites belonging to different orbit at time t, respectively. α denotes the ratio of active MNs to the total number of the nodes.

As a result, the total cost of the binding update process at time t, $C_{BU}(t)$, becomes

$$\begin{aligned} C_{BU}(t) &= 2 \cdot M \cdot H_{MN,LD} \cdot R_{BU}(t) \\ &= 2 \cdot M \cdot H_{MN,LD} \cdot \{R_{CC} + \alpha R_{OHO}\} \end{aligned} \tag{2}$$

B. Local Forwarding

Denoting the hop counts between the satellites in last-hop candidates as H_{sat}, the cost for setting up the local forwarding association between the two satellites is $2 \cdot M \cdot H_{sat}$. In the proposed method, the local forwarding is required after active nodes handover to a satellite on the same orbit. The frequency of such handover is obtained from $(R_{HO} - R_{OHO}) \cdot \alpha$.

As mentioned in Sec. III-C, we should take into account the additional cost for exchanging the covered active nodes list that each other required when the new satellite begins to cover a cell and becomes a last-hop candidate of the cell. If R_{NewSat} denotes the frequency of participation of a newly coming satellite in last-hop candidates, this additional cost approximates $Nsat^2 \cdot H_{sat} \cdot R_{NewSat}$, where N_{sat} denotes the number of single-beam satellites that cover a cell.

Consequently, the total cost of local forwarding at time t, $C_{LF}(t)$ can be expressed as:

$$\begin{aligned} C_{LF}(t) &= (2 \cdot M \cdot H_{sat}) \cdot (R_{HO} - R_{OHO}) \cdot \alpha \\ &\quad + Nsat^2 \cdot H_{sat} \cdot R_{NewSat} \end{aligned} \tag{3}$$

C. Paging

Since a satellite should issue a paging request to its $N_{sat}-1$ neighboring satellites upon a paging initiation, the cost of sending these paging requests between satellites is $2 \cdot M \cdot (Nsat-1) \cdot H_{sat}$.

Considering the paging messages broadcast by the N_{sat} satellites to MNs within their coverage areas, the broadcasting cost is expressed as the product of message size and the number of single-beam satellites: $M \cdot 1 \cdot N_{sat}$.

Since a paging process is performed when an incoming connection arrives at an idle node in a cell, the frequency of paging occurrence in a cell, R_{PAG} is shown as follows:

$$R_{PAG}(t) = D_{node}(t) \cdot l^2 \cdot (1-\alpha) \cdot \lambda \tag{4}$$

where $D_{node}(t)$ and l denote the node density in the cell at time t and the square-shaped cell length, respectively. λ denotes rate of newly coming connections to an idle node.

Consequently, the total cost of paging at time t, C_{PAG}, becomes

$$\begin{aligned} C_{PAG}(t) &= M \cdot \{2 \cdot (Nsat-1) \cdot H_{sat} + N_{sat}\} \\ &\quad \cdot D_{node}(t) \cdot l^2 \cdot (1-\alpha) \cdot \lambda \end{aligned} \tag{5}$$

D. Management Cost of Existing Schemes

1) Mobile IP and Hierarchical Mobile IP: Neither MIP nor HMIP use local forwarding and paging schemes. The difference between these schemes is the destination of the binding updates. In the case of MIP, a node performs binding update to Home Agent (HA) in the Internet. On the other hand, in the case of Hierarchical Mobile IP, a node performs binding update to a local LD in the LEO satellite network.

Consequently, the management cost of MIP, C_{MIP}, and that of HMIP, C_{HMIP} are defined as:

$$C_{MIP}(t) = 2 \cdot M \cdot H_{MN,HA} \cdot R_{HO} \tag{6}$$

$$C_{HMIP}(t) = 2 \cdot M \cdot H_{MN,LD} \cdot R_{HO} \tag{7}$$

where $H_{MN,HA}$ denotes the number of hop counts between a MN and HA host in the Internet.

2) Geographical Location Based Management: Mobility management scheme based on geographical location [3] uses binding update, local forwarding, and paging.

Because binding updates are performed only when nodes move a neighbor cell, the cost of binding update is $2 \cdot M \cdot H_{MN,LD} \cdot R_{CC}$.

Although the equation which defines the cost for local forwarding is the same as that of the proposed method, N_{sat} and H_{sat} are larger than that of the proposed method because of the last-hop ambiguity problem. The cost for paging is the same as the proposed method.

V. Evaluation of the Proposed Method

We evaluate the overhead cost of the proposed mobility management scheme and compare it with that of existing mobility management protocols. A criterion for this evaluation is the sum of the cost for each cell required in a hour. Since we assumed that M takes the same value for all equations for the sake of simplicity, M is not considered in this evaluation.

A. Satellite Related Parameters

Throughout the evaluation, NeLS constellation is used for investigating the required cost for mobility management in the Walker Delta Constellation LEO satellite networks. We use NS-2 for getting parameters shown below for each cell.

- the average number of last-hop candidate satellites for each latitude,
- the average hop counts between last-hop candidates for each latitude,
- timing for change of the members of last-hop candidates for each cell,
- the number of handover for each cell.

Maximum hop counts in NeLS constellation is 11 and we assume that HA exists in the external networks, thus $H_{MN,HA}$ is set to 12. $H_{MN,LD}$ is set to half of $H_{MN,HA}$, because LD is located in nearer position than HA.

B. Mobile Node Related Parameters

We assume that 50 nodes exist in each square-shaped cell, 1 degree on a side from latitude 60 degrees north to latitude 60 degrees south. Note that no nodes are in the area that a few users exist (for example ocean area or high latitude regions). Mobile nodes are assumed to move at 100 km/h.

α depends on λ and duration of each communication. In this evaluation, λ is set to 0.0008. This means that idle nodes become active on an average of three times per hour. In [18], streams in the Internet can be categorized into three types based on their lifetime: Very-Short (VS), Short, and Long-Running (LR). Lifetimes of VS and LR streams are 2 seconds and more than 15 minutes, respectively. Short streams have less than 15 minutes lifetime, but only a few streams have more than 2.5 minutes lifetime according to a traffic analysis appeared in [18]. Most of the streams in the Internet are VS or Short. Therefore, we assume that 70% of communications are VS lasting up to 2 seconds, 1.5% is LR lasting up to 20 minutes, and the rest is Short lasting up to 2.5 minutes. For each second in evaluation, α is calculated based on λ and duration of communication.

C. Evaluation Results

Figure 5 presents the evaluation results. The figure demonstrates that the proposed method and the geographical location based mobility management significantly outperforms MIP and HMIP in terms of the management cost in the case that cell size is more than 2 degrees. As the cell size is increased, management cost of the two methods is decreased. It is because that smaller cell incurs higher rate of cell boundary crossing of nodes, and this results in higher frequency of binding updates. For all cell sizes, the proposed method is more efficient than the geographical location based mobility management.

In Fig. 6, we show the effect of ratio of VS and LR communications for the two method. Management cost of the two method and the cost reduction ratio by the proposed method are illustrated in the figure. Although increase of LR communication makes more MNs active and this may result in

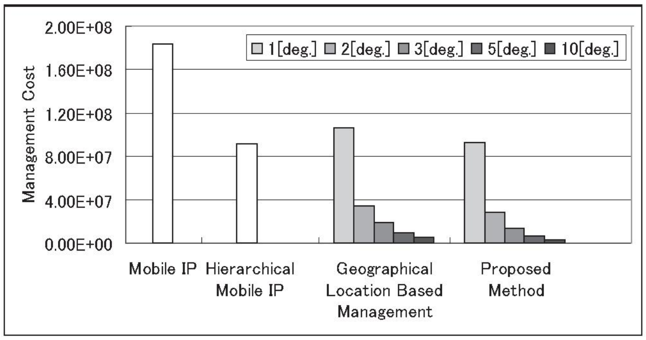

Fig. 5. Management Cost for Each Cell Size

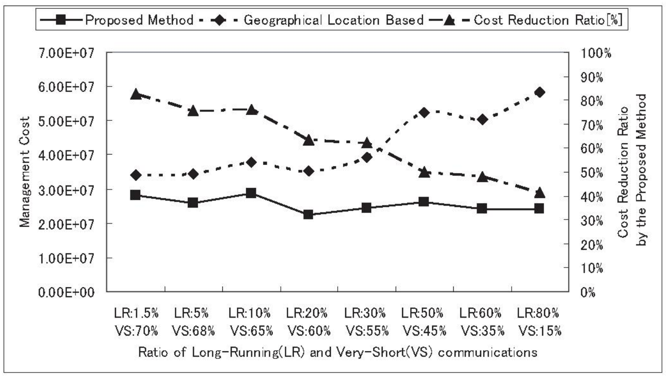

Fig. 6. Effect of Ratio of Long-Running and Very-Short Communications

bursty and frequent binding update occurrence as mentioned in III-B, evaluation result indicates that the proposed method works more efficiently as the ratio of LR communication increases. This is because that last-hop ambiguity generates more local forwarding cost for geographical location based scheme. On the other hand, as shown in Figs. 1, 2, and 4, both the number of last-hop candidate satellites and hop counts between last-hop candidates can be reduced by using orbital information. Therefore, the local forwading cost of the proposed method is still small if active MNs increase. This is the reason why the proposed method can outperform the geographical location based mobility management scheme.

Consequently, we conclude that the proposed method provides the efficient mobility management scheme in IP/LEO satellite networks in the case of appropriate cell sizes.

VI. Conclusions

In this paper, we proposed a mobility management scheme under the last-hop ambiguity problem in IP/LEO satellite networks. Simulation results showed that the geographical location of a node is not sufficient to find the correct last-hop satellite of the node.

To overcome the last-hop ambiguity problem, a new method was developed. The proposed method exploits orbital information of the satellite connected with the node in addition to geographical location information for limiting the last-hop candidate satellites. Because only the satellites belonging to a same orbit can be last-hop candidates by using proposed method, hop counts between the last-hop candidates is also decreased. This results in significant reduction of the cost required for local forwarding after handovers.

Comparison of the proposed method performance to that of Mobile IP, Hierarchical Mobile IP, and the geographical location information based management have been provided. Performance evaluation results demonstrated the efficiency of the proposed method in reducing the mobility management cost.

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